Innovations in 3-D Neutronics Analysis for Fusion Energy Systems

Paul P.H. Wilson
Fusion Technology Institute
U. Wisconsin-Madison

UW Plasma Seminar
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THE UNIVERSITY of WISCONSIN MADISON

UW Fusion Neutronics Team

5 Faculty/Scientists
1 Visiting Scientist
1 Post-doc
1 Researcher

5 Graduate Students

Nuclear Design & Analysis

L. El-Guebaly

M. Sawan

T. Bohm

(B. Smith)

(A. Ibrahim)

P. Phruksarojanakun

D. Henderson

(B. Kiedrowski)

E. Marriott

(C. Aplin)

P. Wilson

3-D Geometry Capability Enhancements

Radiation Transport & Effects Code Development

(R. Slaybaugh)

T. Tautges
(ANL)

Overview

- Why Fusion Neutronics?
- Transport methods
- Activation methods
- Applications
  - High Average Power Laser IFE
  - ARIES-Compact Stellarator
  - ITER Benchmark
  - ITER First Wall & Shield
- Summary

Role of Neutronics in Fusion System Design

- Source term for engineering design
  - Heat removal/electricity generation
  - Tritium breeding
- Source term for engineering challenges
  - Damage to materials
    - Manufacturing for replaceable components
    - Shielding of sensitive components
  - Accident analysis
- Source term for health physics and waste management
  - Activation & photon source

Typical Neutronics Problems

- Fixed 14.1 MeV neutron source
- Dominated by
  - Shielding/deep penetration
  - Labyrinth streaming
- Nuclear responses depend on detailed neutron flux spectrum
- Combined neutron/photon problems for nuclear heating responses

Transport
Analysis for Conceptual Design

- 1-D/2-D calculations
  - Deterministic
  - Rapid iteration in design process
  - Require expertise in developing valid approximations
- 3-D calculations
  - Monte Carlo
  - Confirm validity of 1-D/2-D calculations
  - Identify hi-fidelity variations in results

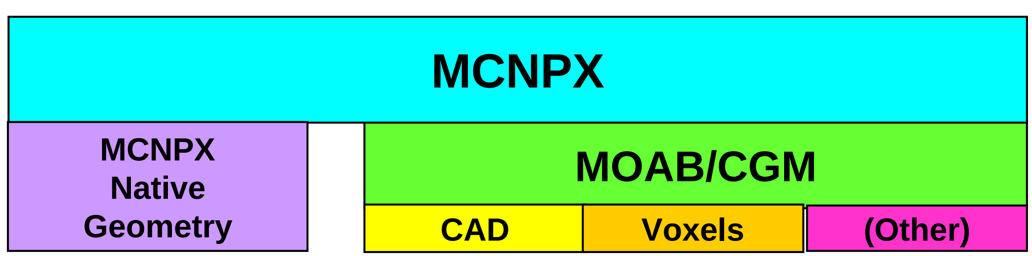
Monte Carlo Neutronics

- MCNP(X) software from LANL
- Complex geometry
  - 2^{nd} order analytic surface descriptions
- Continuous energy treatment
- Structured mesh tallies for high-fidelity results
- Variance reduction techniques for improving computational performance

DAGMC

Direct Accelerated Geometry Monte Carlo

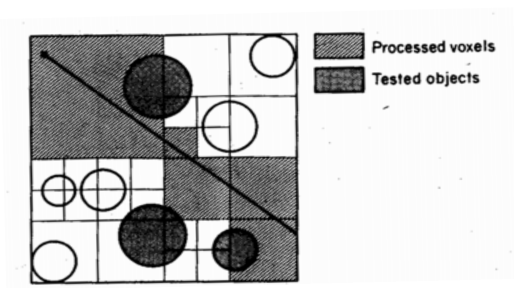
- Use MOAB or Common Geometry Module (CGM) to interface MC code *directly* to CAD (& other) geometry data
  - Previous efforts found CAD-based ray tracing to be too slow (20-50x)
  - What's new?
    - Implement ray-tracing approximations to reduce calls to exact CAD function
    - Can be implemented once & reused for all representations



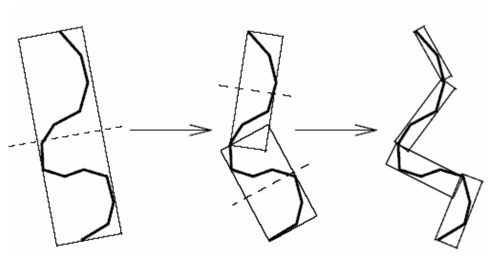
Accelerations

- Key issue: accelerate ray-tracing (fewer & faster)

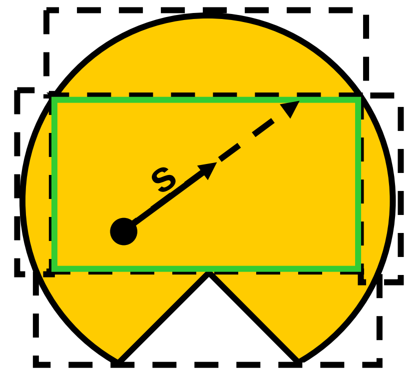
- Key technology: oriented bounding box trees



Hierarchical Subdivision



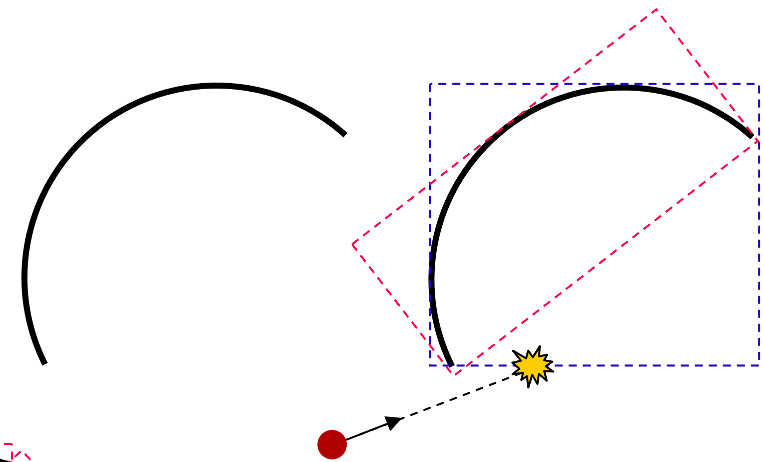
Oriented Bounding Box



Inside Bounding Box (w/ path length limit)

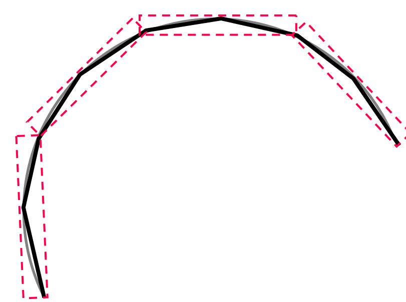
Hierarchical Oriented Bounding Box

- Axis-aligned bounding box often larger than necessary

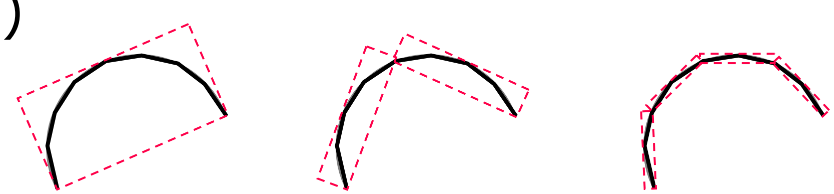


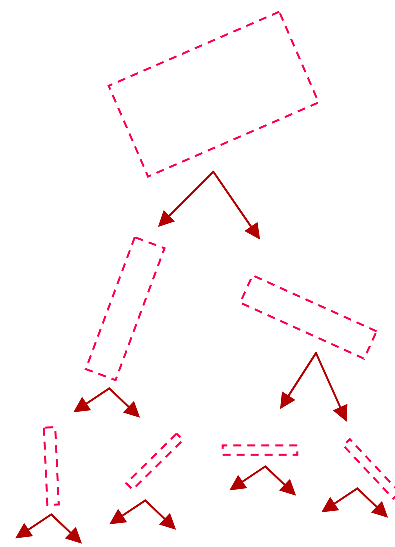
- *Oriented* bounding box makes smaller boxes

- OBB on facets allows finer-granularity boxes



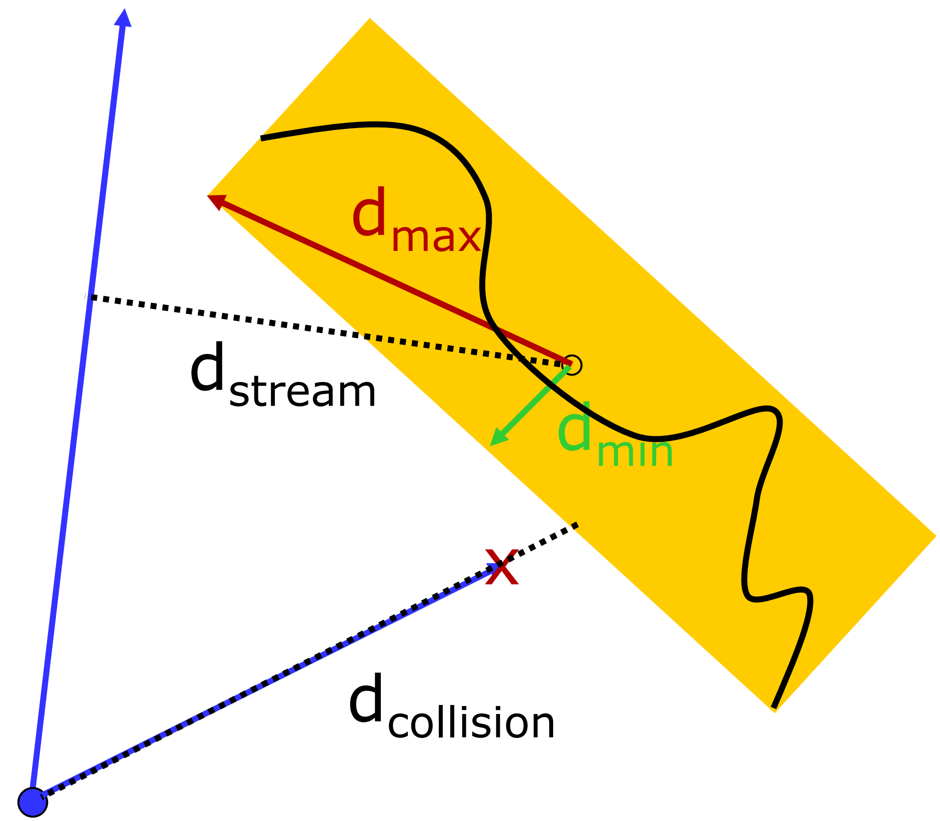
- Tree of OBBs reduces # tests to log(n)





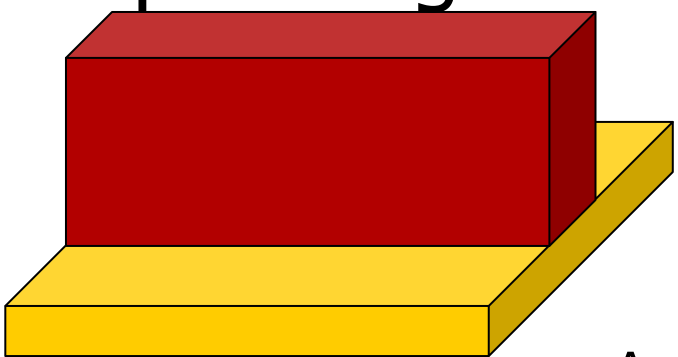
Bounding Box Accelerations

- Simple (inexpensive) bounding box test
  - Streaming distance to closest approach
  - Collision distance to closest approach

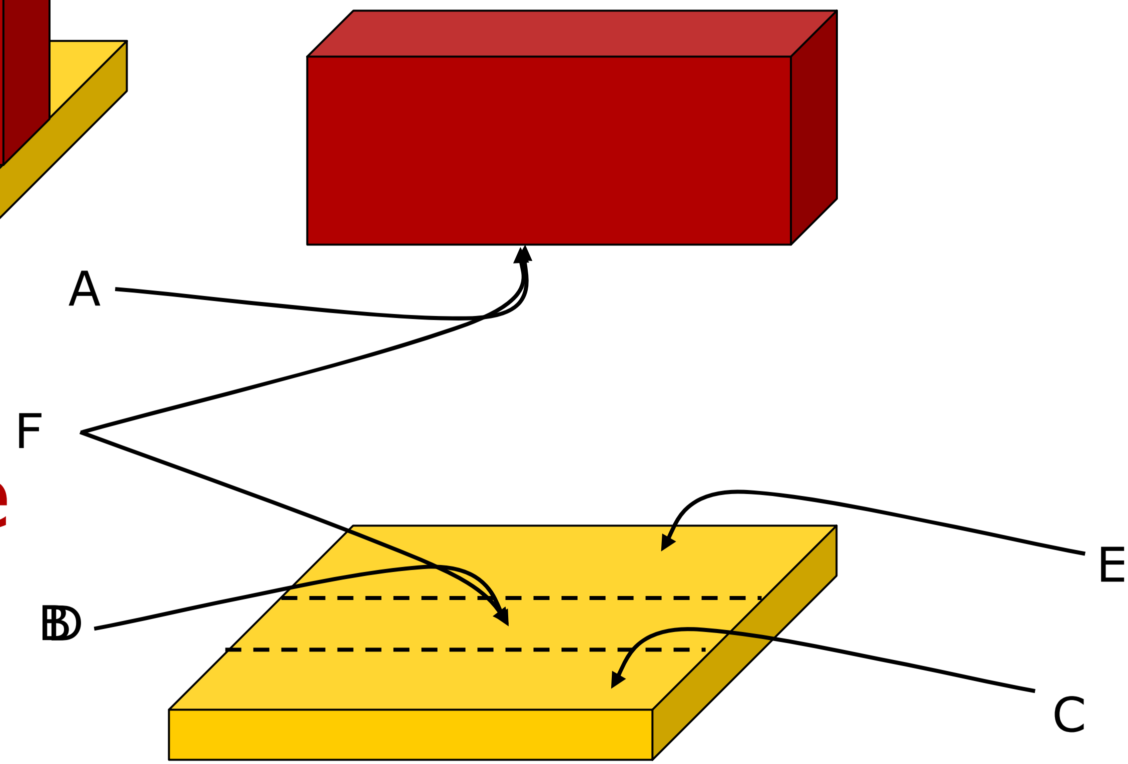


Non-manifold Geometry

- Imprinting



- Merging
- Each surface in max. 2 cells



Activation

- Tracking isotopic inventories over time
  - Stiff system of ODE’s (a la Bateman)
- Pulsed/intermittent irradiation histories
  - Steady-state approximations can introduce errors
- High fluences
  - Long activations chains
  - Loops are possible
- Widely varying flux magnitudes and spectra
  - Solutions vary spatially
- Waste management issues
  - Problem isotopes can be from rare initial constituents

ALARA

Adaptive Laplace & Analytic Radioactivity Analysis

- Physical modeling features
  - Loop unrolling
  - Global truncation
  - Reverse calculation ('adjoint')
  - Cross-section driven = no fixed reaction table
  - Built-in responses: waste disposal rating, adjoint dose folding
- Mathematical features
  - Matrix solutions for efficient pulsing
  - Element-wise adaptive mathematical method
    - Bateman vs. Laplace expansion vs. recursive Laplace inversion

MCise
Monte Carlo Isotopic Simulation Engine

- Complex flow paths & loops
- Continuously varying sources
- Chemical separation
- Variance reduction
  - Forced reactions
  - Reaction splitting
- Automated VR adjustment
- Global Figure of Merit

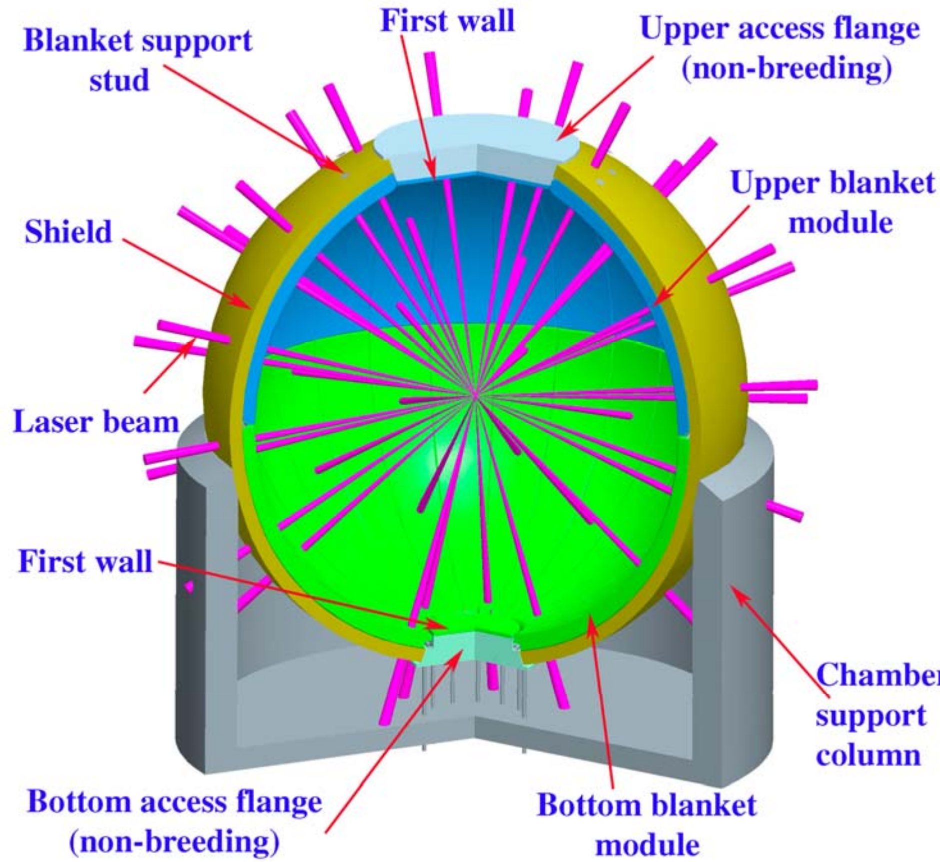
Applications

- High Average Power Laser IFE
- ARIES Compact Stellarator
- ITER Benchmark
- ITER First Wall & Shield

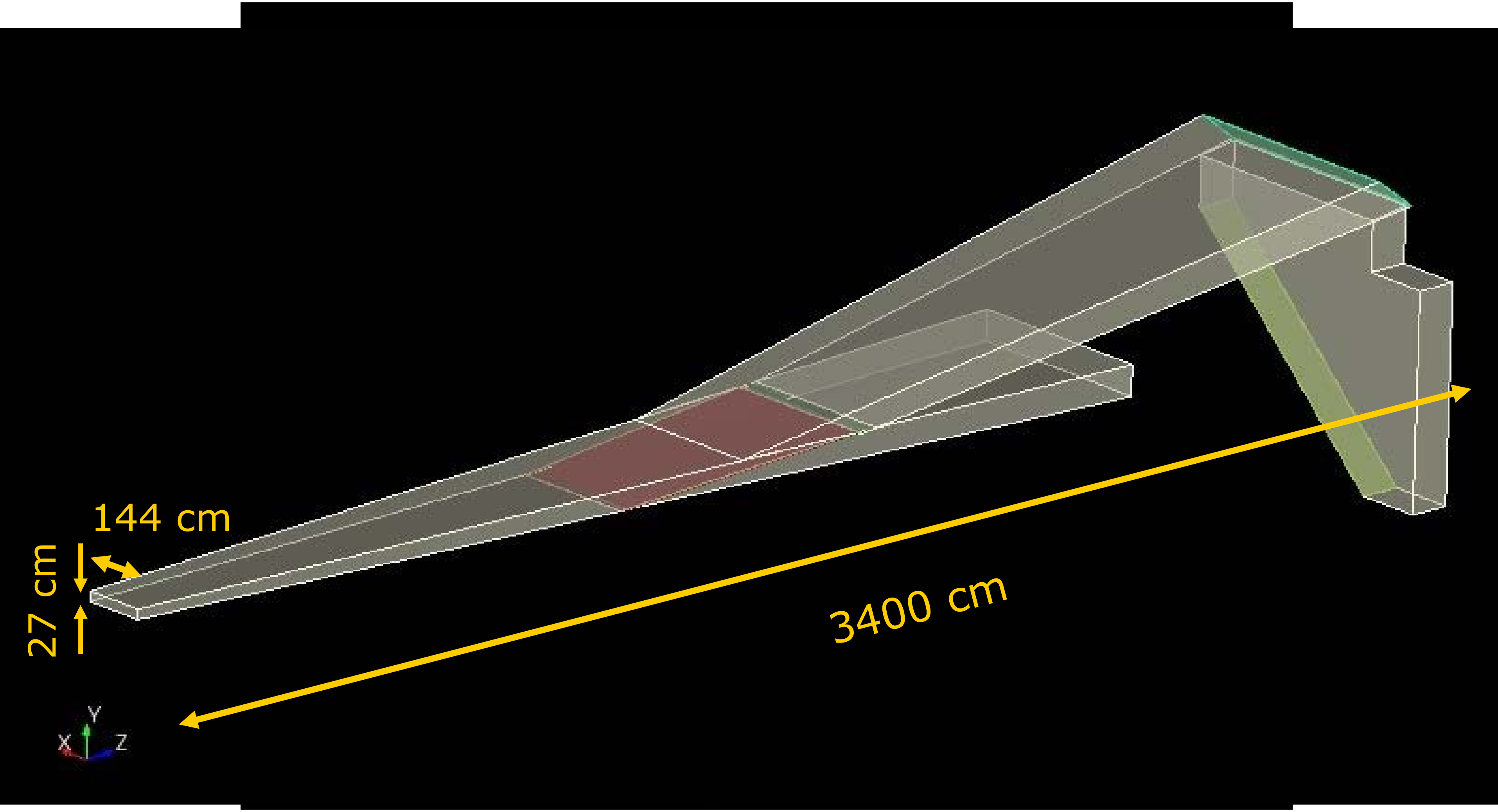
Final Optics

- Laser beams must have direct line of sight to target

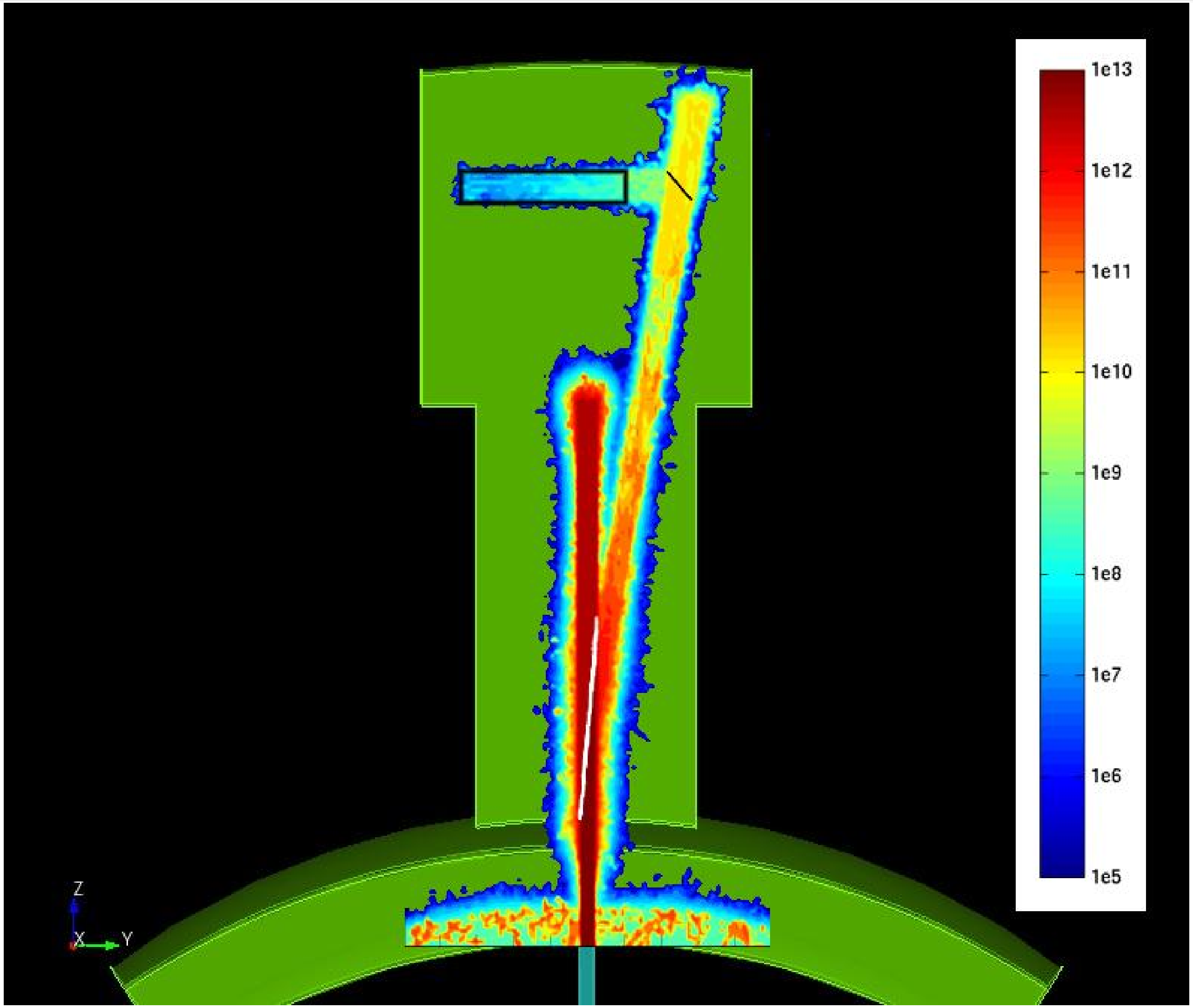
∴ Mirrors in direct line of sight from target
  - Efficient mirrors are sensitive to radiation damage



Final Optics



HAPL mesh tally w/ geometry



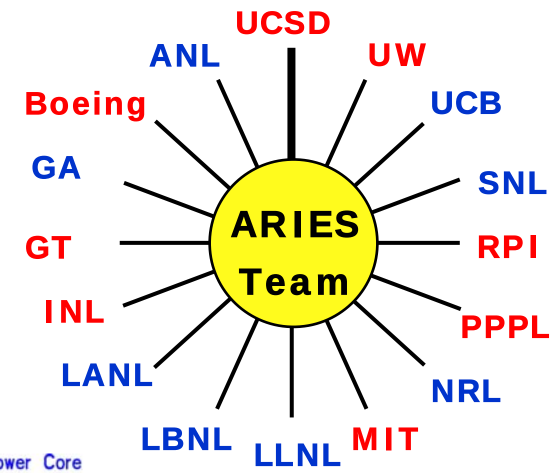
The ARIES Project

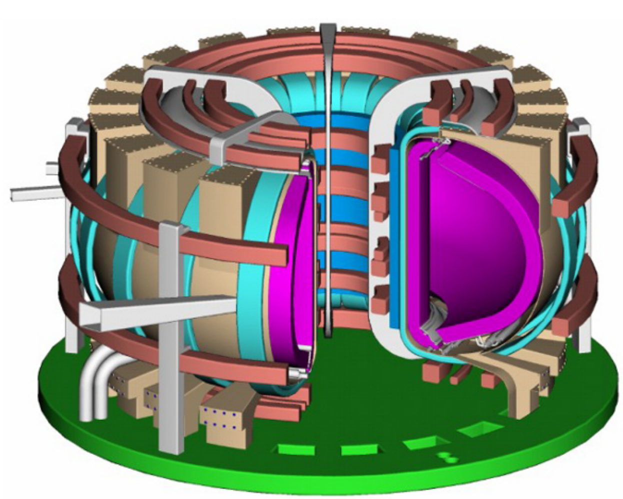
ARIES Mission

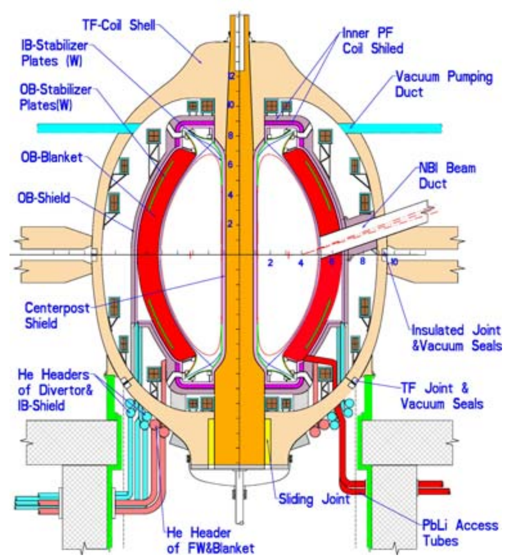
Perform advanced integrated design studies of long term fusion energy embodiments to identify key R&D directions and provide vision for the U.S. fusion program.

ARIES Goal

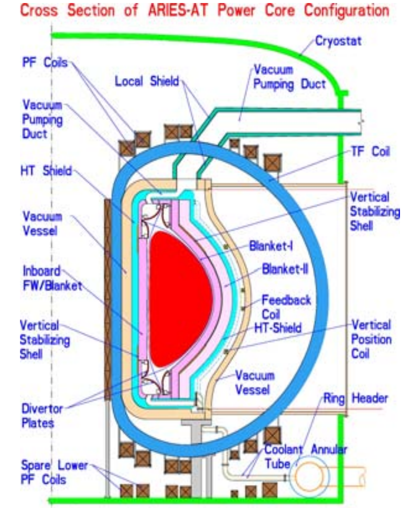
Demonstrate that fusion power can be a safe, clean, and economically attractive option.







Elevation View of ARIES-ST Power Core

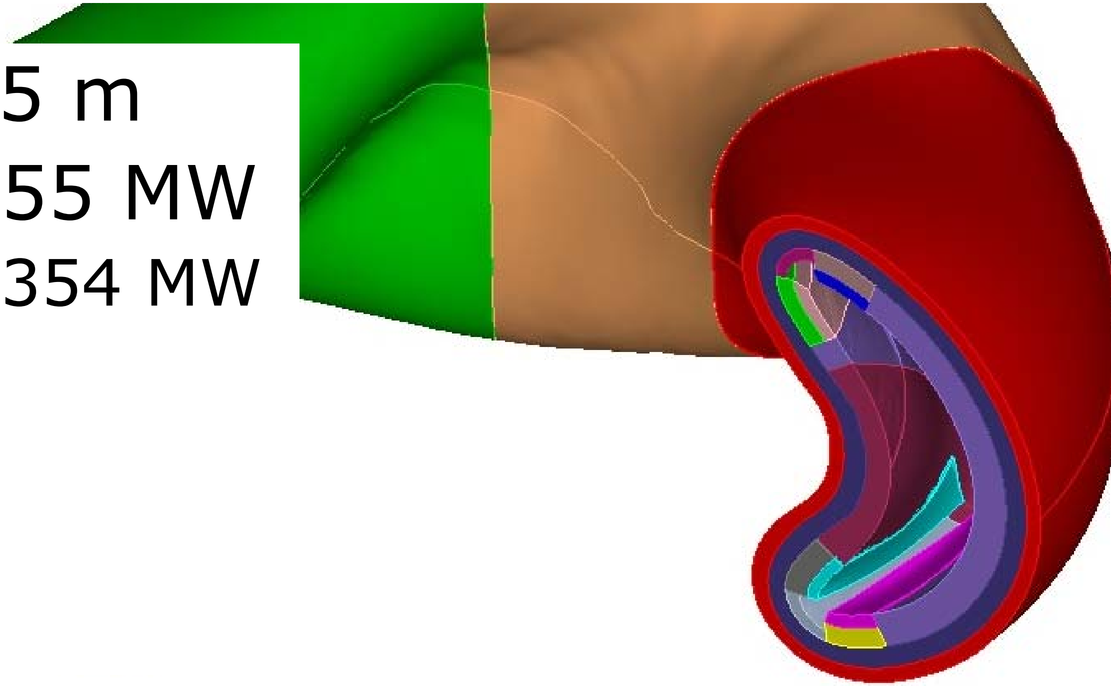


Cross Section of ARIES-AT Power Core Configuration

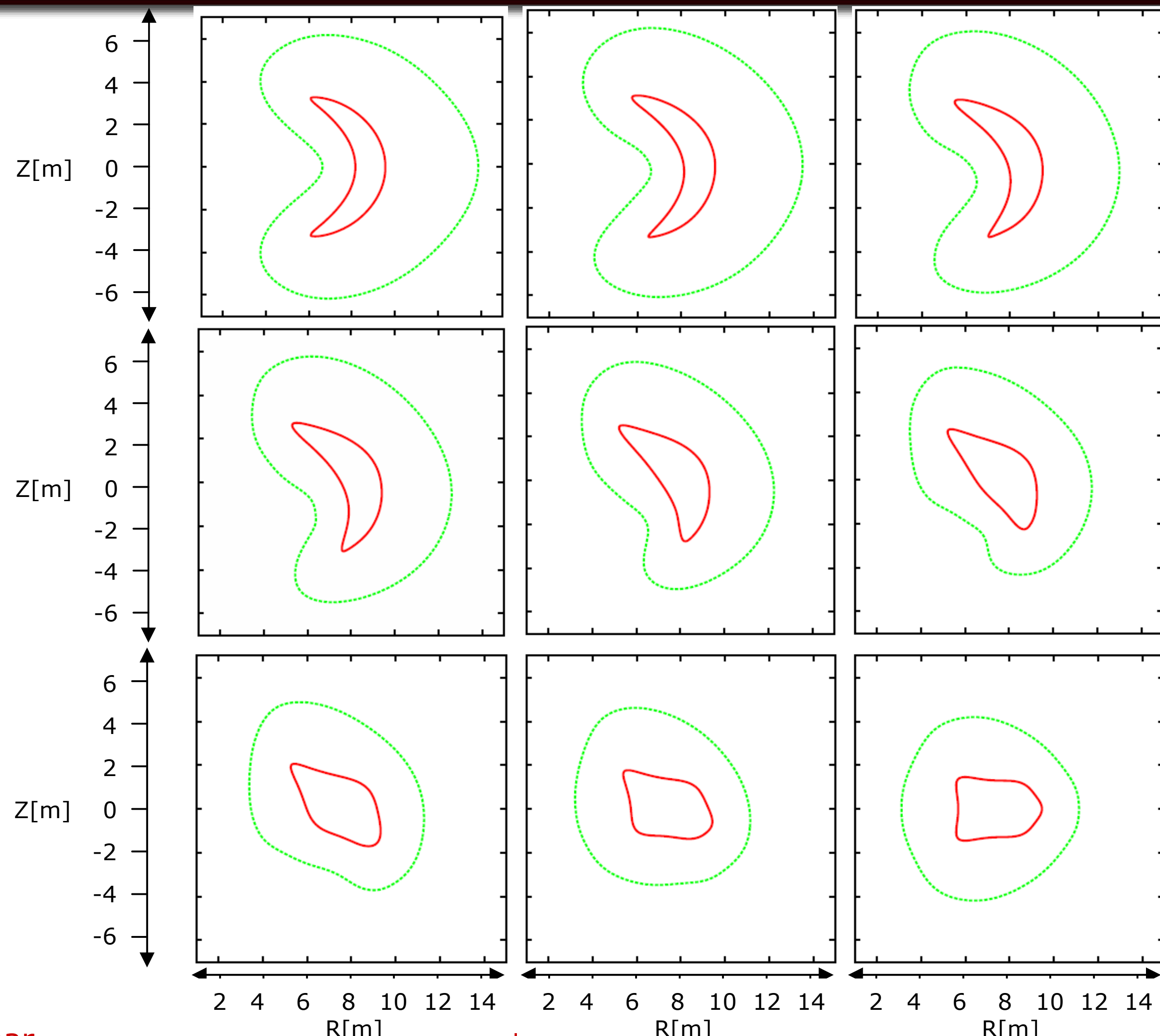
ARIES Compact Stellarator

- ARIES-CS has a complex 3-D geometry
  - Plasma surfaces based on high-order Fourier series expansion
  - Machine surfaces based on offsets from *last closed magnetic surface*

- Major radius: 7.75 m
- Fusion power: 2355 MW
  - Radiative power: 354 MW
- 5cm SOL
  - except divertors (30cm SOL)
- FW area: 727 m^2



Plasma & Mid-Coil Profiles



Note: data from L-P Ku (PPPL)

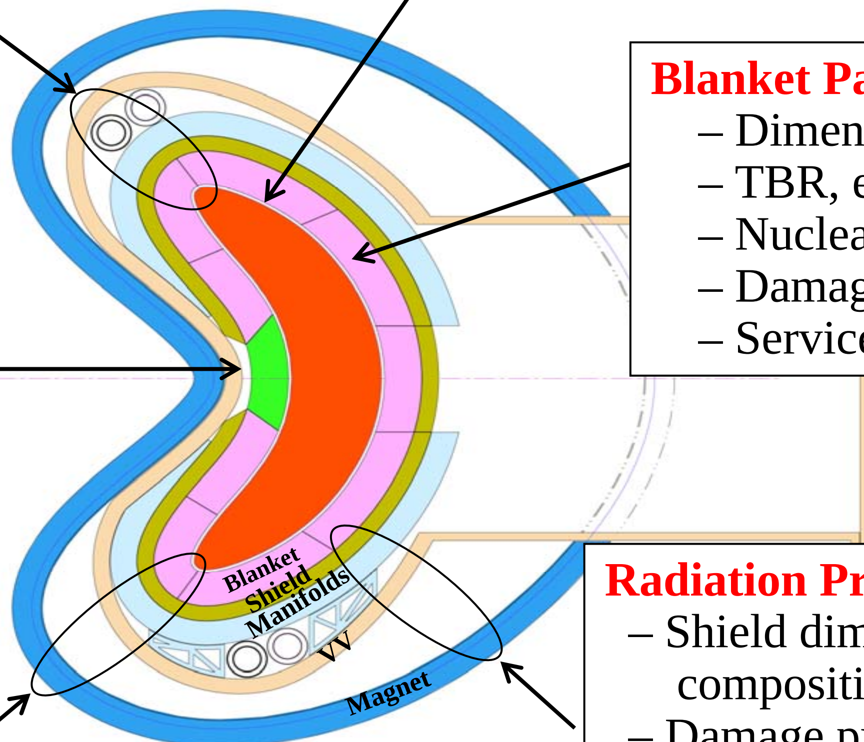
Nuclear R&D Areas

Radial Build Definition:
- Dimension of all components
- Optimal composition

Neutron Wall Loading Profile:
- Toroidal & poloidal distribution
- Peak & average values

Blanket Parameters:
- Dimension
- TBR, enrichment, M_n
- Nuclear heat load
- Damage to FW
- Service lifetime

Reduced blanket size and High-performance shielding module at Δ_{min}



Activation Issues:
- Activity and decay heat
- Thermal response to LOCA/LOFA events
- Radwaste management

Radiation Protection:
- Shield dimension & optimal composition
- Damage profile at shield, manifolds, VV, and magnets
- Streaming issues

Need 3-D Source Definition

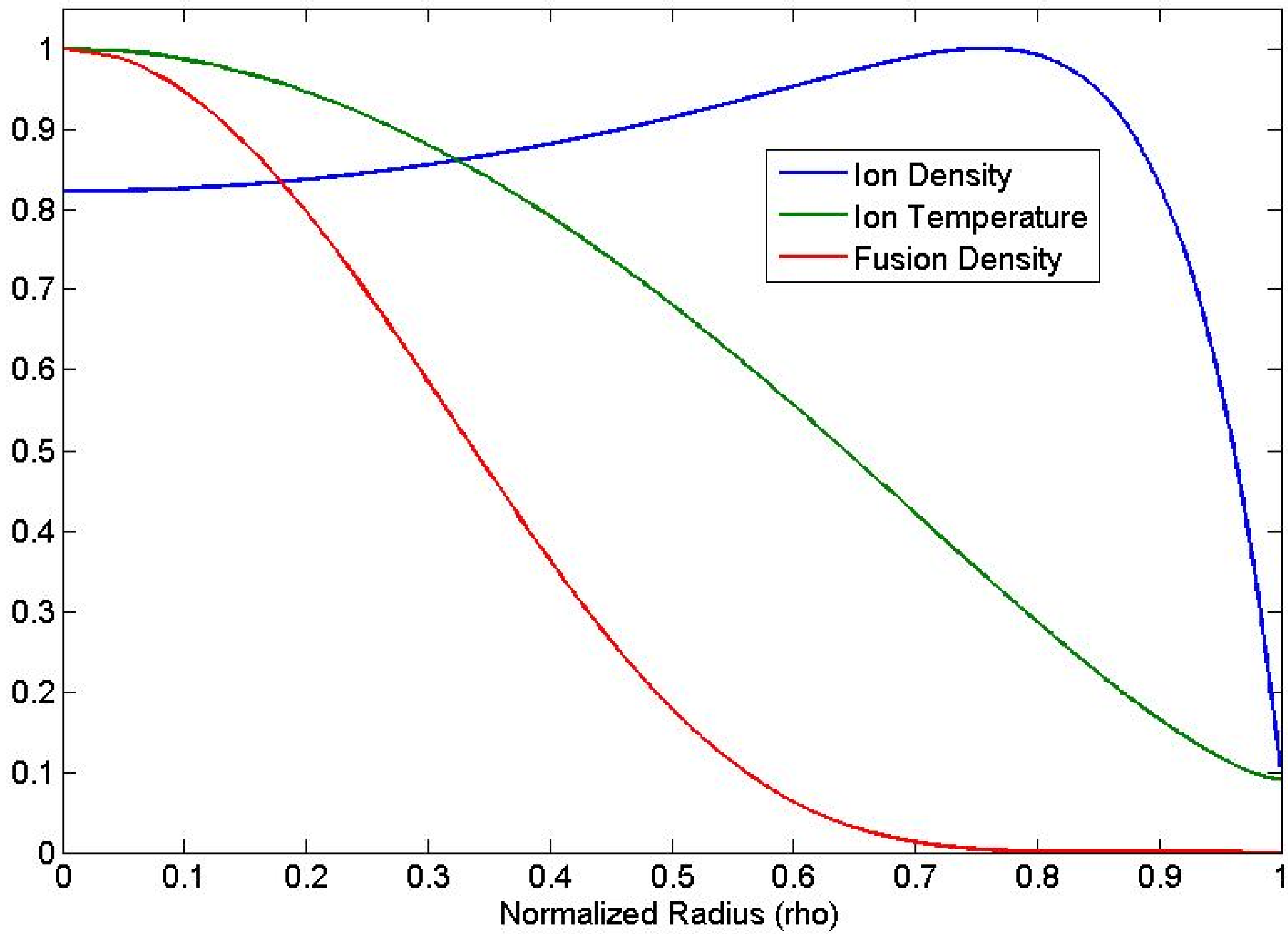
- 1-D modeling
  - Uniform source acceptable approximation
- 3-D modeling enabled by new neutronics tool
  - Source distribution becomes limiting approximation in model analysis

Neutron Source Methodology

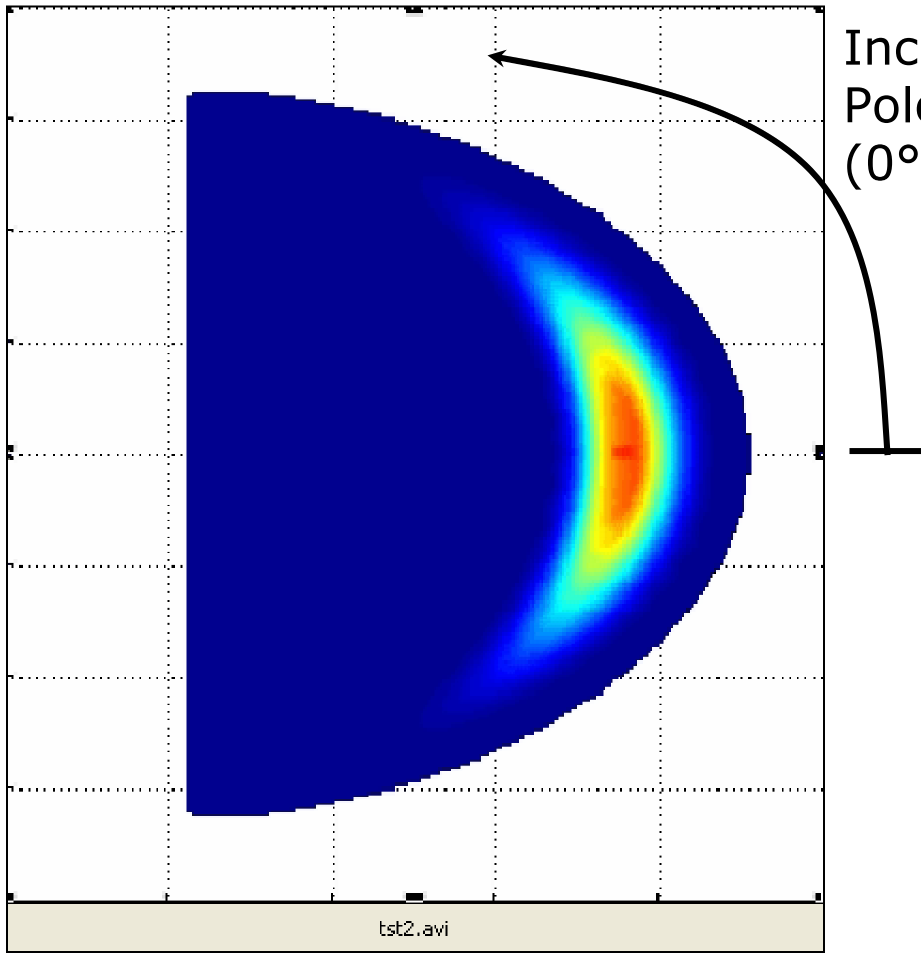
- Generate hex mesh in real space from uniform mesh in *flux coordinate space*
  - Idealized (R,θ,ϕ) toroidal system
  - Degenerate hexes at magnetic axis
- Generate cumulative distribution function for source density in hex mesh
- Sample for which hex mesh cell
- Sample for position in chosen mesh cell
  - Sampling a location in an arbitrary hex, subject to an interpolated PDF is analytically challenging

Fundamental Source Density

Note: based on Data from J. Lyon (ORNL)



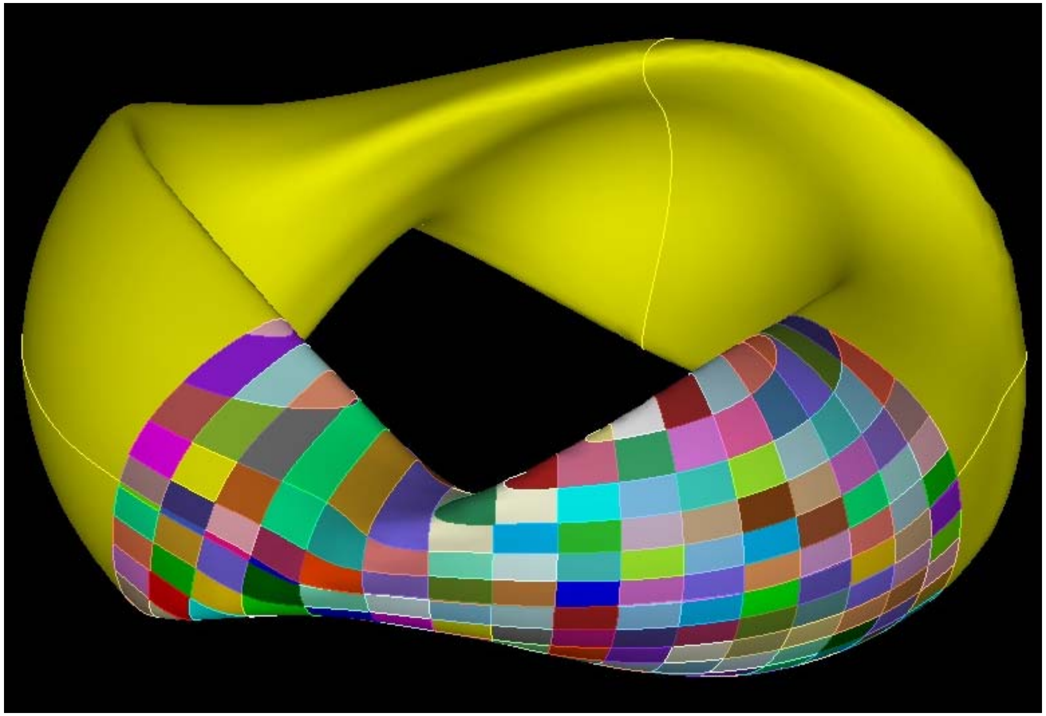
Source Probability Map



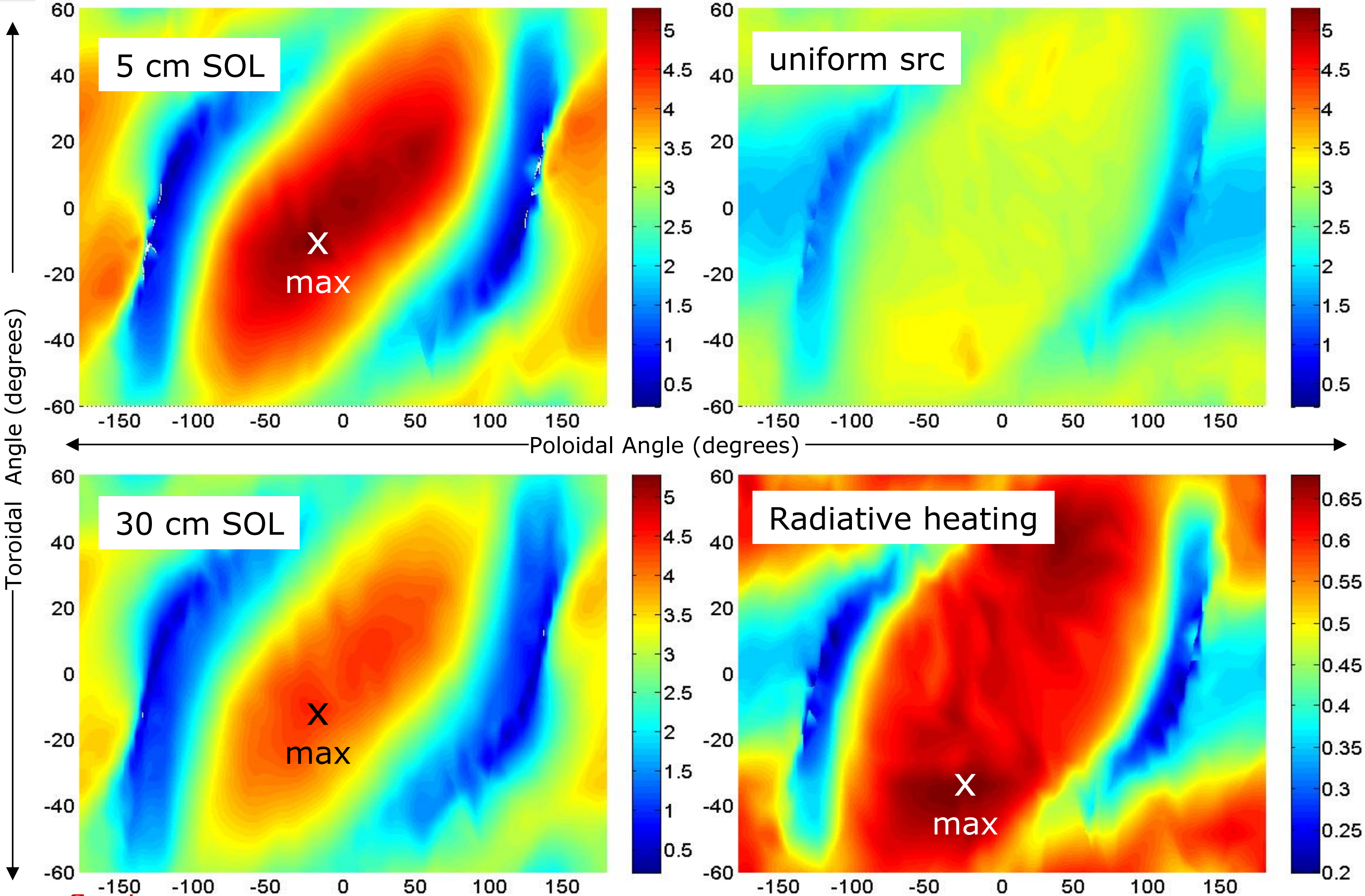
Increasing
Poloidal Angle
(0° at O/B midplane)

Results and Analysis

- Calculate NWL on surface grid
  - Some statistical variation
- Transform (x,y,z) coordinates of each patch to (θ_P, ϕ_T)
- Interpolate results on 200 x 200 uniform grid in (θ_P, ϕ_T)



NWL Maps (colormaps in MW/m²)



NWL Summary

	Peak (Min) [MW/m²]	Toroidal Angle (degrees)	Poloidal Angle (degrees)
Real 3-D Source [5 cm SOL]	5.26 (0.32)	-11 (-4)	-18 (-116)
Real 3-D Source [30 cm SOL]	4.42 (0.42)	-11 (-11)	-25 (122)
Uniform Source	3.56	-49	-21
Rad. Heating	0.68 (0.2)	-34 (11)	-17 (-117)

ARIES-CS Tritium Breeding Ratio